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The Properties and Genesis of Four Soils Derived from Basaltic Ash, Mauna Loa, Hawaii[1]

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ABSTRACT: The properties and genesis of four soils derived from basaltic ash are presented. In a sequence of increasing rainfall and elevation (decreasing temperature), there was a decrease in the values for *p*H, cation exchange capacity, the exchangeable bases, and base saturation. On the other hand, there was an increase in the values for carbon: nitrogen, clay percentages, free iron oxides, and the ratio of exchangeable calcium: exchangeable magnesium. There was also a general increase in the carbon content and in the values of the 15-bar water with increasing rainfall. In comparison with soils derived from andesitic ash, the soils derived from basaltic ash had high amounts of sand and silt, high *p*H values, and high base saturation for similar rainfall. They also had lower organic matter, carbon: nitrogen ratios, cation exchange capacity, and 15-bar water values. These differences are attributed to the younger age and to the higher contents of calcium and magnesium of the basaltic ash.

THE DEPOSITS of volcanic ash throughout the world are generally andesitic or rhyolitic in composition. Basaltic ash is much less common and is usually localized in occurrence immediately around its source volcano. Presumably, the lower viscosity of the less siliceous, basaltic magma allows water vapor and other volcanic gases to escape with less than explosive force and is, therefore, conducive to the production of much more lava than ash.

On the island of Hawaii, however, the active volcano Kilauea has produced extensive deposits of basaltic ash that lie on the slopes of the older, quiescent volcano Mauna Loa, in the vicinity of the small towns of Naalehu and Pahala. Soils formed in this ash in a range of climates from hot and very dry to warm and humid have properties that set them apart from the many other soils derived from volcanic ash in Hawaii.

This study provides information about a sequence of four soils developed in this basaltic ash and examines the extent to which the properties of the soils relate to the somewhat unusual nature of their parent material.

DESCRIPTION OF THE VOLCANIC-ASH PARENT MATERIAL

Thick deposits of basaltic ash occur in the Kau district in the south and southeastern part of the island of Hawaii. They are formed, according to Fraser (1960), by phreatic explosions from cones and rift areas of the Kilauea volcanic complex. Sinking and faulting in the volcanic area presumably caused the magma to rise and allowed ingress of groundwater, and perhaps seawater, into the magmatic chamber. The eruptions then occurred with explosive force.

The deposits have been called Pahala Ash by Fraser (1960), although this name was used previously by Stearns and Macdonald (1946) to

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TABLE 1

SOME GENETIC FACTORS OF THE SOILS

SOIL SERIES	ELEVATION (feet)	MEDIAN ANNUAL RAINFALL (inches)	SOIL TEMPERATURE (°F)	VEGETATION
Pakini	250	20	74	grasses and shrubs
Naalehu	850	50	72	sugarcane
Moaula	1,700	60	70	sugarcane
Alapai	2,250	80	69	sugarcane

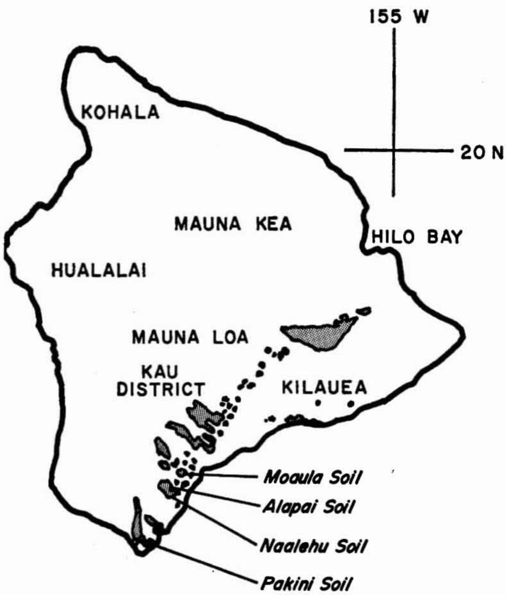

FIGURE 1. Map of the island of Hawaii showing distribution of volcanic ash parent material and locations of sampling sites.

apply to several ash deposits on the island of Hawaii that originated from several volcanoes. Fraser and Stearns and Macdonald agree that the ash in the Kau district that is the parent material of the sequence of soils studied in this work originated from Kilauea. The distribution of this ash is shown in Figure 1. Macdonald (Stearns and Macdonald 1946: 199–201) described this ash as consisting of pale brown or brownish green pumiceous glass fragments. In some places, these fragments have altered to yellowish brown or orange palagonite. The phenocrysts, which resemble those in basaltic lava, are olivine and plagioclase; the plagioclase ranges from sodic bytownite to medium labradorite. The color depends upon the amount of alteration, which in turn is largely the result of the amount of vegetation and rainfall (Wentworth 1938, Stearns and Macdonald 1946).

THE SOILS

Four soils, Pakini, Naalehu, Moaula, and Alapai, were collected from the southern slopes of Mauna Loa in the vicinity of the town of Naalehu, Hawaii (lat 19°4′13″ N, long 155° 13′18″ W), from an elevation of 250 to 2,250 feet. The approximate locations of the sample sites are shown in Figure 1.

Some of the genetic factors of the soils are shown in Table 1. The median annual rainfall at each sample site was determined from the rainfall gauges located near the sample sites, whereas the mean annual temperature was determined from soil temperatures taken at a depth of 50 inches. All of the soils are well drained. Three of the soils are cultivated for sugarcane production. Profiles described by the personnel of the Soil Conservation Service, United States Department of Agriculture, have been presented by Hassan (1969).

METHODS

The chemical data of the Pakini and Naalehu soils were analyzed by the Soil Survey Laboratory in Riverside, California. The bulk density of these same soils was determined by the Hawaiian Sugar Planters' Association.

For the Moaula and Alapai soils, the freshly collected samples were crushed gently and passed through a 2-mm sieve. The sieved sample was then thoroughly mixed and subsampled. One subsample was air-dried and further ground to pass through a 100-mesh sieve, thoroughly mixed, and stored for C, N, free Fe oxide, and differential thermal analysis (DTA). Another subsample was kept moist in plastic bags and was used to determine *p*H, cation exchange capacity (CEC), and particle size distribution. Moist samples were analyzed because some of the properties of volcanic ash soils change when the soils are dried.

For all of the samples, particle size distribu tion was carried out according to the method of Kilmer and Alexander (1949). The clay fraction was analyzed with a Norelco Philips X-ray diffractometer with CuK_α radiation and a Ni filter. Differential thermal analyses were carried out on all samples. The 100-mesh, air-dried soil was kept for 48 hours in a vacuum desiccator, saturated with $Mg(NO_3)_2$ to keep the relative humidity at about 57 percent. A 0.10-gram sample was mixed thoroughly with 0.09 gram of calcined alumina and then was analyzed by means of a Stone DTA apparatus at the rate of 10° C rise per minute from 20° to 1,000° C. Selected clay minerals were also analyzed. Nitrogen gas was used to suppress the oxidation of organic matter.

Soil *p*H was determined in H_2O (1:1 or 1:5) and normal KCl (1:1 or 1:5) by means of a Beckman *p*H meter. Organic C was determined by the Walkley and Black (1934) method with a recovery factor of 77 percent. Free Fe oxides were determined by the method of Kilmer (1960). Total N was determined by the Kjeldahl distillation method. In the determination of CEC and exchangeable cations, neutral, normal ammonium acetate solution served as the replacing agent for the cations, and 10-percent NaCl solution was used to exchange the ammonium ions absorbed on the exchange sites. The 15-bar water was determined by means of a pressure membrane apparatus.

RESULTS AND DISCUSSION

Results of the analyses are shown in Table 2. In the sequence of soils, values for *p*H, CEC, exchangeable Ca, Mg, K, Na, and base saturation (BS) decrease with increasing rainfall and elevation. Values for C:N, clay percentages, free Fe oxides, and the ratio of exchangeable Ca:exchangeable Mg increase with increasing rainfall and elevation. In the three cultivated soils, Naalehu, Moaula, and Alapai, percentage C also increases with increasing rainfall. Values of 15-bar water increase with rainfall and elevation to the Moaula soil and then remain about the same in the Alapai soil. Pakini soil is much sandier than the others, but the sand and silt fractions, containing considerable volcanic glass, are chemically reactive and contribute to the CEC and water-holding capacities.

Calcium is the main exchangeable cation, other than H, throughout. Potassium is a significant exchangeable cation only in the Pakini soil, and Mg only in the Pakini, Naalehu, and Moaula soils. Sodium remains a significant exchangeable cation throughout the sequence.

Free Fe oxides are positively correlated with percentage clay and 15-bar water values and negatively with CEC. The decrease in CEC with increasing rainfall, increasing clay, and increasing Fe oxides is worthy of note. It results from the replacement of chemically reactive volcanic glass and allophane by kaolin and gibbsite, as the rainfall and degree of weathering increase. The free Fe oxides probably form as positively charged colloids, causing the CEC to decrease as their amounts increase.

Although the deeper ash layers in these soils are older than the surface layers, there are only slight visual and statistically nonsignificant trends that could be related to this fact.

Loganathan and Swindale (1969) reported on a sequence of soils from andesitic ash on the slopes of Mauna Kea, Hawaii. The sequence, from Apakuie to Maile, was arranged in order of increasing rainfall and temperature. The present sequence, from Pakini to Alapai, is arranged in order of increasing rainfall and decreasing temperature. The two sequences of soils have similar trends for *p*H, BS, percentage organic C, C:N, free Fe oxides, and clay percentages. These trends are, therefore, more significantly related to rainfall, which has the same trend in both sequences, than they are to temperature, which does not.

In comparison with the sequence of soils from andesitic ash, this sequence of soils from basaltic ash has higher amounts of sand and

TABLE 2

SUMMARY OF THE PROPERTIES OF THE SOILS

SOIL	DEPTH (cm)	pH 1:1 H_2O	pH 1:1 KCl	ORGANIC CARBON (%)	C:N	TOTAL CEC* (meq/100 g)	EXCHANGEABLE CATIONS (meq/100 g) Ca	Mg	K	Na	BS† (%)	FREE IRON OXIDES (%)	PARTICLE SIZE SAND (%)	SILT (%)	CLAY (%)	15-BAR WATER (%)	BULK DENSITY (g/cc)	CLAY MINERALOGY
Pakini‡																		
Ap	0–8	6.7	5.7	5.3	11	51.0	22.6	14.0	7.4	1.0	88	4.4	47.1	45.3	7.6	26.4	0.82	allophane, kaolin, mica
A12	8–20	6.6	5.3	3.89	11	45.4	17.9	12.0	4.7	1.6	80	5.5	47.4	47.1	5.5	26.9	0.74	allophane, kaolin, mica
A3	20–41	7.0	5.8	2.68	12	60.6	31.1	18.9	4.0	2.9	94	6.8	55.5	41.7	2.8	36.9	0.75	allophane, kaolin, mica
B21	41–74	7.6	6.4	1.51	13	68.1	37.5	23.5	4.9	2.9	100+	5.7	48.8	48.5	2.7	36.2	0.76	allophane, kaolin, gibbsite, mica
B22	74–114	8.1	6.9	0.83	12	61.3	36.4	28.7	5.2	6.1	100+	5.0	52.2	45.2	2.6	28.3	0.90	allophane, kaolin, gibbsite, mica
Cca	114–152	8.1	7.2	0.66	12	57.2	30.8	28.4	6.1	12.0	100+	5.1	53.3	41.8	4.9	25.6	0.97	allophane, kaolin, gibbsite, mica
Naalehu§																		
Ap	0–51	5.4	4.5	3.29	13	45.8	17.2	9.1	0.7	0.7	60	5.9	19.0	52.4	28.6	28.6	0.87	allophane, kaolin
B21	51–79	5.8	4.8	1.97	12	50.2	22.8	11.7	0.7	1.0	72	7.5	19.8	52.0	28.2	41.6	0.85	allophane, kaolin
IIB22	79–91	6.6	5.6	0.90	11	63.1	33.7	19.2	0.5	1.8	87	9.2	19.0	53.1	27.9	37.7	0.79	allophane, kaolin
IIIB23	91–135	6.7	5.6	0.60	11	63.6	35.8	23.8	0.3	2.1	97	9.7	22.4	51.4	26.2	55.6	0.46	allophane, kaolin
IVC	135–165	6.6	5.7	0.47	n.d.	67.6	34.4	26.5	0.2	1.9	93	7.9	24.7	49.6	25.7	47.8	0.51	allophane, kaolin
Moaula																		
Ap	0–23	4.9	4.5	7.89	14	43.8	13.8	3.7	0.7	0.9	43	7.3	15.5	54.8	29.7	42.5	n.d.‖	allophane, kaolin
B21	23–43	6.2	5.3	7.88	13	45.4	19.2	4.2	0.1	3.2	58	11.8	17.6	52.9	29.5	54.7	n.d.	allophane, kaolin
B22	43–58	6.2	5.4	2.53	12	48.8	19.0	3.1	0.2	2.6	51	13.6	18.8	50.2	31.0	52.6	n.d.	allophane, kaolin
B23	58–79	6.3	5.5	1.90	12	47.0	15.8	3.9	0.1	1.9	46	13.6	18.7	51.1	30.2	37.6	n.d.	allophane, kaolin, gibbsite
B24	79–102	6.2	5.4	1.81	13	46.2	18.6	5.5	0.1	2.3	57	14.3	14.2	54.8	31.0	45.2	n.d.	allophane, kaolin, gibbsite
B25	102–122	6.3	5.4	1.18	12	52.0	18.2	5.3	0.1	2.6	50	13.4	15.0	56.2	28.8	38.7	n.d.	allophane, kaolin, gibbsite
B26	122–137	6.4	5.5	1.10	13	53.2	18.1	3.7	0.1	2.5	45	14.5	19.2	51.4	29.4	55.9	n.d.	allophane, kaolin, gibbsite
B27	137–165	6.4	5.5	1.13	12	53.9	19.3	3.5	0.1	2.9	47	13.4	20.1	50.2	29.7	45.5	n.d.	allophane, kaolin, gibbsite
B28	165–188	6.4	5.7	0.65	13	46.2	16.5	7.0	0.1	2.4	56	12.3	22.0	48.7	29.3	42.7	n.d.	allophane, kaolin
Alapai																		
Ap1	0–18	4.8	4.3	11.90	15	39.3	8.8	3.3	0.5	0.5	33	7.8	14.7	51.8	33.5	38.1	n.d.	allophane, kaolin, gibbsite
Ap2	18–38	5.8	5.2	6.32	15	42.1	6.3	0.3	0.4	0.3	17	12.5	15.3	51.0	33.7	55.0	n.d.	allophane, kaolin, gibbsite
B1	38–69	6.4	5.4	2.93	14	40.0	5.5	0.6	0.2	0.4	17	12.7	16.0	49.8	34.2	46.2	n.d.	allophane, kaolin, gibbsite
B21	69–92	6.1	5.1	3.49	14	51.0	10.0	0.1	0.5	1.5	24	13.8	18.9	46.8	34.3	41.7	n.d.	allophane, kaolin, gibbsite, mica
B22	92–109	6.2	5.4	4.02	14	39.9	9.0	0.1	0.5	1.3	27	15.4	17.6	48.8	33.6	44.5	n.d.	allophane, kaolin, gibbsite, mica, quartz
B23	109–127	6.0	5.2	3.51	13	35.3	6.5	0.3	0.4	1.3	24	14.7	18.5	44.6	36.9	41.9	n.d.	allophane, kaolin, gibbsite, mica
B24	127–145	6.0	5.1	3.74	13	41.6	7.1	0.3	0.5	1.2	22	16.3	16.2	51.4	32.4	44.3	n.d.	allophane, kaolin, gibbsite, mica
B25	145–168	6.2	5.3	3.19	11	46.8	7.2	0.9	0.5	1.9	22	15.9	21.4	50.1	28.5	50.5	n.d.	allophane, kaolin, gibbsite, mica
B26	168–188	6.0	5.4	1.91	14	41.8	3.1	0.3	0.1	0.5	9	16.1	21.6	49.5	28.9	54.7	n.d.	allophane, kaolin, gibbsite, mica

* CEC: cation exchange capacity.

† BS: base saturation.

‡ Chemical data of Pakini and Naalehu soils are from Sato et al. (1973: 104–105).

§ Bulk density data of Pakini and Naalehu soils are from Sato et al. (1973: 104–105).

silt, higher *p*H values, and higher BS for similar rainfalls. It also has lower organic matter contents, C:N, CEC values, and 15-bar water values for similar rainfalls. These differences between the two sequences relate to the age of the ash, which is generally younger in the sequence reported here, and to the difference in the contents of Ca and Mg ions, which are higher in the basaltic ash. Further discussion of the properties of these soils is presented in the following paragraphs.

Pakini Soil

The surface horizon of the Pakini soil is 8 to 10 inches (20 to 25 cm) thick, is dark brown in color, and has a weak platy structure. The subsurface horizons are brown and yellowish brown, are lighter in color than the A horizon, and have weak prismatic structures. The deepest horizon is a calcic horizon. The soil has a sandy texture, although the values for CEC and 15-bar water indicate that the coarser fractions contain aggregated clay or contain chemically active and probably glassy surfaces.

Values for *p*H and BS are high and increase with depth. The *p*H values measured in KCl are at least 1 *p*H unit below values measured in H_2O.

Percentage organic C values are high for a soil in such a climate. They decrease with depth. The C:N ratios are lower than for other soils in the sequence but are higher than for soils from alluvium or residium in similar climates.

Cation exchange capacity values are very high, averaging about 60 meq throughout the profile. The values for the two upper horizons are noticeably lower, 51.0 and 45.4, respectively, than those for the lower horizons.

The ratio exchangeable Ca: exchangeable Mg decreases with depth and approaches 1.0 in the calcic horizon. This suggests the possible presence of some dolomite in this horizon. The proportion of exchangeable Na increases with depth.

Free Fe oxides are much lower than for most Hawaiian soils. The clay in the soil is allophane with possibly a little gibbsite at depth (see Figures 2*a*, *b*; 3*a*, *b*). The DTA patterns of the two upper horizons have smaller low-tempera-

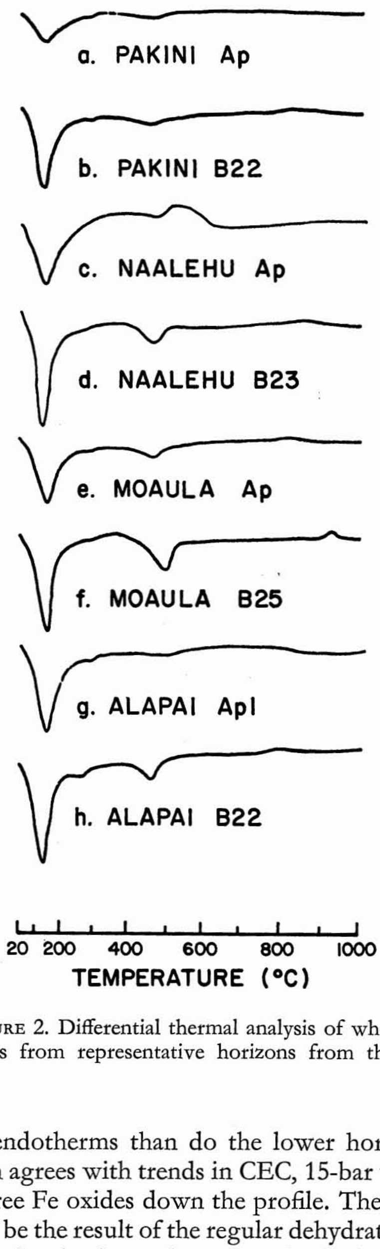

FIGURE 2. Differential thermal analysis of whole soil samples from representative horizons from the four soils.

ture endotherms than do the lower horizons, which agrees with trends in CEC, 15-bar water, and free Fe oxides down the profile. The trend could be the result of the regular dehydration of the surface horizons that occurs in the hot, arid climate in which the soil occurs, or the result of the competition between organic colloids and cations for the active surfaces, or the result of the change in reactivity with *p*H, or perhaps to the occurrence of different layers of ash in the profile.

The Pakini soil has been classified as a

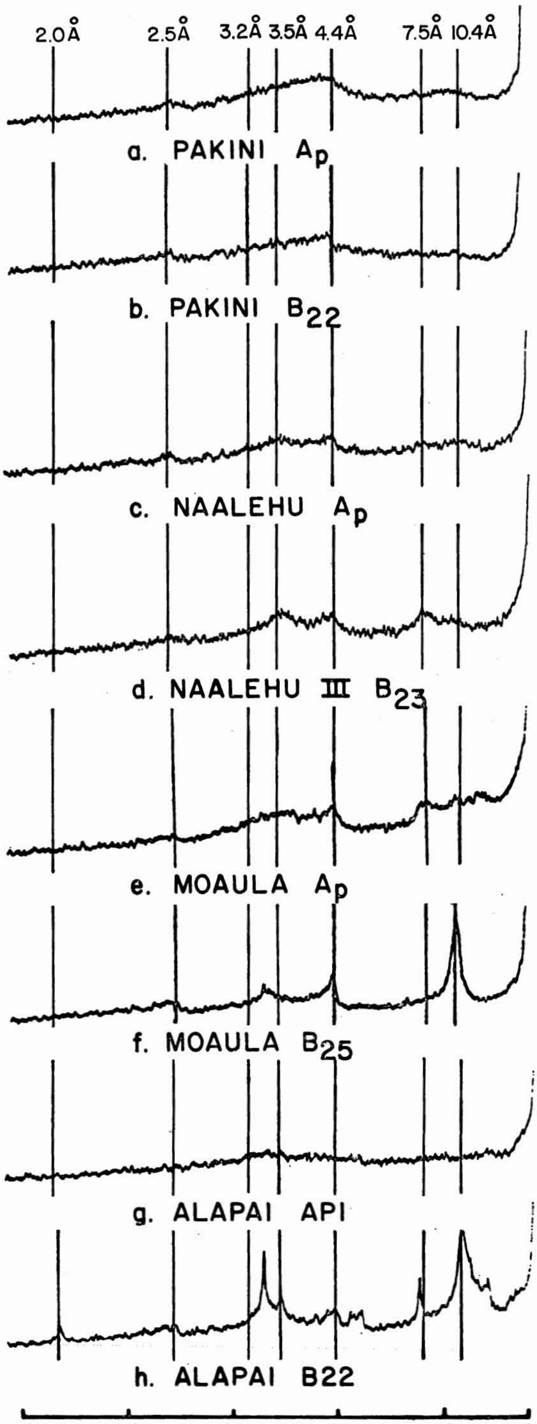

FIGURE 3. X-ray diffraction patterns from clay fractions ($<2\ \mu$) of representative horizons from the four soils.

medial, isohyperthermic Entic Eutrandept. The analyses and profile descriptions support this classification.

Naalehu Soil

The surface horizon of the Naalehu soil is 20 inches (50 cm) thick, is dark brown in color, and has moderate granular structure. The subsurface horizons appear to coincide with different layers of ash, are reddish brown in color, and have weakly prismatic structures or are structureless.

Textures are silty clay loam, and there is less than 30-percent experimentally determined clay. Cation exchange capacity and 15-bar water values indicate that the coarser fractions contain chemically active surfaces.

Values for *p*H range from 5.6 to 6.8 and increase abruptly between the B21 and IIB22 horizon. The change may be a function of the parent material difference, or may be the result of cultivation practices, with ammonium sulfate being used as a N source. Base saturation ranges from 60 to 97 percent and shows a similar abrupt change below the B21 horizon. Values for *p*H measured in KCl are about 1.0 to 1.2 units lower than values measured in H_2O.

Percent organic C values decrease with depth from 3.29 in the A horizon to 0.5 in the C horizon. The values are lower than those for the drier Pakini soil, which occurs under a continuous grassy vegetation. C:N ratios are 11 to 13 as for the Pakini soil.

Cation exchange capacity values are high, averaging about 60 meq throughout the profile. The values for the two upper horizons are lower than those below. The ratio exchangeable Ca: exchangeable Mg decreases regularly with depth toward a value of 1.0.

Free Fe oxides range from 5.9 to 9.7 percent and increase abruptly below the B21 horizon. The clay in the soil contains allophane and a disordered, hydrated kaolin mineral (see Figures 2*c*, *d*; 3*c*, *d*).

The Naalehu soil is classified as a medial, isohyperthermic Typic Eutrandept. The analyses confirm this classification.

Moaula Soil

The soil probably formed in several layers of ash like the Naalehu soil farther down the slope. Soil horizons, distinguished by small differences in color and compaction, may coincide with these layers, but the chemical and physical properties do not show trends that could reasonably be ascribed to different parent materials.

The surface horizon is 6 to 12 inches (15 to 30 cm) thick, dark brown in color, and has a strong subangular blocky structure. The subsurface horizons are reddish brown in color, are weakly smeary, and have moderate or weak subangular blocky structures. The lowest three horizons have few to common light colored mottles, which may be the weathered remnants of volcanic lapilli that are noticeable in other horizons.

The texture is silty clay loam throughout the first seven horizons and clay loam in the lowest two horizons. Clay contents, experimentally determined, are lower than the 15-bar water values would suggest. There is, however, distinctly more clay and less sand than in the Naalehu profile.

The *p*H value of the surface horizon is 4.9, this probably being the result of fertilization practices. The *p*H values throughout the rest of the profile range from 6.2 to 6.4 and average 6.3 percent. Base saturations range from 43 to 58 and average 50 percent. The value for the surface horizon is noticeably lower at 43 than are the remaining values, this again probably being the result of fertilization practices. Values for *p*H determined in KCl vary from 0.4 to 0.9 units below values determined in H_2O.

Cation exchange capacity values are lower in the Moaula soil than in the Pakini and Naalehu soils. They range from 44 to 54, and are highest in the B26 and B27 horizons. There is no trend with depth either in CEC or in the ratio exchangeable Ca: exchangeable Mg. The latter ratio, however, is much higher throughout the profile than in the Pakini and Naalehu soils.

Percentage organic C ranges from 7.9 in the surface to 0.7 in the B28 horizon and decreases with depth. The C:N ratio ranges from 12 to 14, and is noticeably higher than in the Pakini and Naalehu soils.

Free Fe oxides vary from 7.3 to 14.5; they are lowest in the Ap and B21 horizons where the ash layers are also the youngest. Clay minerals are allophane and a hydrated kaolin. In the two top horizons, the kaolin mineral is disordered. Below that it is clearly halloysite (see Figures 2*e*, *f*; 3*e*, *f*).

The Moaula soil has been classified as a Hydric Dystrandept. The BS of the surface horizon is 43 percent. However, unlike most Dystrandepts, the BS increases below the surface and averages 50.3 throughout the profile. It is quite possible that the lower BS in the surface is caused by agricultural practices. According to the 1970 draft of the *United States Soil Taxonomy*, the Moaula soil is classified as a thixotropic, isothermic Hydric Dystrandept.

Alapai Soil

The surface horizons of the Alapai soil are 15 inches (38 cm) in thickness, are dark brown and dark reddish brown in color, are weakly smeary, and have a moderate subangular blocky structure. The subsurface horizons are dark brown and dark reddish brown in color, generally are moderately smeary, have moderate subangular blocky structures, and contain fragments of volcanic lapilli. The lowest two horizons sampled, below 57 inches (145 cm), contain variously colored mottles, which are most probably weathered lapilli fragments.

The texture is silty clay loam throughout the first seven horizons and clay loam in the lowest two horizons. The experimentally determined clay varies from 28.5 percent at depth to 37 percent in the middle of the profile, and averages higher than in any of the other soils sampled. The 15-bar water values are high and suggest that the coarser fractions contain chemically active surfaces.

The *p*H value of the surface horizon is 4.8, probably as a result of fertilization practices. The *p*H values throughout the remainder of the profile range from 5.8 to 6.4 and average 6.1 percent. Base saturation ranges from 9 to 33 and averages 22 percent. There is no particular trend on BS throughout the profile. Values for *p*H determined in KCl are 0.5 to 1.0 units below those determined in H_2O.

Percent organic C values range from 11.9 to 1.9 and decrease generally down the profile. The C:N ratio ranges from 13 to 15 (with one exception) and is a little higher than in the Moaula soil.

Cation exchange capacity values range from 35 to 51, and average 42 percent. These are the lowest values in the sequence of soils. The ratio exchangeable Ca:exchangeable Mg is much higher than in the other soils of the sequence. Exchangeable Na exceeds the exchangeable Mg in the profile.

Free Fe oxides range from 7.8 in the surface horizon to 16.3 in the lower B horizon. There is a slight trend for the values to increase down the profile.

Clay minerals are mainly allophane, hydrated halloysite, and gibbsite (see Figures 2*g*, *h*; 3*g*, *h*). The B2 horizons, particularly the B22, contain micas, hydrated mica, and even some quartz, probably because these have been surface horizons in the past when tropospheric dust was being deposited on the ground in Hawaii (cf. Jackson et al. 1971). The soil is classified as a thixotropic, isothermic Typic Hydrandept. The analyses confirm this classification.

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